FINAL TECHNICAL REPORT

for

STUDY OF COSMIC RAYS IN THE SOLAR ENVIRONMENT

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ABSTRACT

The major objective of the research is to establish the correct equations that govern the behavior of cosmic rays (both of solar and of galactic nature) in the presence of the solar environment plasma. The ultimate aim is that of constructing the transfer function that relates the local cosmic beam with that in the interstellar space. At every stage in the inference, close comparison is to be made between the theoretical deductions and the observations available. Suggestions concerning pertinent observations are made wherever possible.

We summarize below the papers prepared during the year towards this objective. A major outcome of the year's collaboration between the Greenbelt and the ARAP groups is an estimate of the interstellar spectrum of cosmic rays and of the X-radiation expected from HI clouds as a consequence of the energy transferred to them by the cosmic rays.

INTRODUCTION

Our research effort has two primary objectives: (1) the correct description of the interaction of cosmic rays with the interplanetary medium, and, therefore, the determination of the primary cosmic ray spectrum, and (2) the understanding of the X-radiation from galactic sources and the prediction of intensity and polarization in experimentally attainable bands.

These objectives closely parallel the experimental work carried out at the Energetic Particles Laboratory in Greenbelt.

The common theoretical problem that underlies both objectives of our work is that of understanding the motion of energetic charged particles (in general relativistic) in the presence of the turbulent plasma and magnetic field that constitutes the interplanetary and interstellar medium. Given the correct description of the motion of the charged particles, it is then possible, in principle, to calculate the radiation that they emit.

A significant understanding of cosmic rays during any particular phase of their lifetime (e.g., their modulation by the solar cavity) requires an insight into the previous phase (a boundary condition in the modulation example). Thus, while we study the sun as a modulator of the cosmic ray beam, it is essential to understand how this spectrum is generated. A possible source of the cosmic rays are the galactic supernovae. A useful prototype is the Crab Nebula which can be studied in far greater detail than other galactic supernovae. We have reviewed the information available on the Crab Nebula with this objective in mind. A physical picture of this object has emerged that should allow us to make plausible predictions with regard to the radiation observable in frequency bands not yet detected. The effect of the interstellar medium is clearly an essential ingredient in constructing the boundary condition for the modulation problem.

A major outcome of this year's work can be summarized as follows. From analysis of the modulation undergone by the cosmic

ray beam (based on either the diffusion-convection model or magnetic Brownian motion estimates), it has been possible to estimate the cosmic ray spectrum in the interstellar medium. This study indicates that measurements of the X-ray band emitted by the H_I regions of the galaxy give direct information on the primary spectrum of the cosmic rays. These measurements would thereby offer a strong check on the theoretical transfer function, which is one of our primary objectives.

Our results are summarized in some detail in the next section by giving the abstracts of 14 papers completed during the year, and by summarizing some of the unpublished work.

RESULTS

The results that have been obtained are summarized below by giving the abstracts of papers prepared during the year.

1. An Electrostatic Model for Stellar Winds by S.H. Lam and G. Sandri

ARAP Report No. 97 and presented at the AIAA 5th Aerospace Sciences Meeting, New York, January 1967

In the present paper we study the dynamics of stellar winds as a collisionless plasma flow problem. We first present a rigorous formulation of the problem (with spherical symmetry) for an arbitrary ratio of the electron to ion escape flux, J_e/J_i. Since the collisionless assumption is valid only far away from the star where the trajectories of the charged particles are essentially radial, we invoke the "radial-trajectory" approximation to simplify our analysis. Our analysis shows that (1) in the absence of an interstellar plasma no steady solution which is uniformly quasi-neutral exists, (2) by including the dynamics of the interstellar plasma a solution can be found for an arbitrary value of J_e/J_i, including the physically interesting case of $J_e/J_i = 1$, and (3) a "double-edged" sheath is found to exist in the stellar wind flow field. The plasma is quasi-neutral everywhere except in this sheath across which the electrostatic potential varies substantially. The location of the sheath is found to depend sensitively on the interstellar plasma density.

2. Statistical Mechanics of Charged Particles in the Presence of Magnetic Irregularities by M. Fibich and G. Sandri

ARAP Report No. 82 and presented at the Washington, D.C. APS Meeting, April 1967

We introduce a model to describe the interaction of cosmic rays (either of solar or of galactic origin) with the solar wind. The model consists in replacing the magnetic irregularities in the wind by highly localized scattering centers. The statistical mechanical theory corresponding to this model is traced in detail from Liouville's theorem through a kinetic equation to the conventional diffusion equation. The statistical nature of the fields within the magnetic irregularities is described in terms of an appropriate Fourier analysis.

3. Relativistic Charged Particles in an Electromagnetic Field I: Uniform, Stationary Fields by A. Klimas and G. Sandri

ARAP Report No. 100

A new operator formalism is introduced for describing the

4-space motion of a charged particle in uniform stationary electric and magnetic fields. Projection operators are constructed from the field strength tensor and its dual, which allow the separation of the world velocity of the charged particle into two orthogonal, 4-velocities with two degrees of freedom each. It is demonstrated that one of these velocities always contains the gyratory part of the motion of the particle, and the other is the world velocity of the particle's guiding center. Exact solutions of the equations of motion for each of the projected velocities are obtained and combined to give a general solution for the trajectory of a particle in an arbitrary uniform field configuration. These solutions are used to demonstrate the connection between the projected 4-velocities and the 3-space guiding center velocity.

4. Classical Relativistic Mechanics of Particles with a Two-body Interaction by A. Klimas and G. Sandri

Presented at the Washington, D. C. APS Meeting (April 1967)

A Lorentz invariant mechanics of particles interacting via a two-body scalar potential is formulated. The rest mass of each particle is allowed to be time-dependent. Relativistically deep-bound states are discussed within the framework of this theory. Our formalism is a natural basis for relativistic statistical mechanics since the equations of motion are $9N$ first-order equations with a single standard time variable.

5. The Crab Nebula by A. Klimas

Presented at the NASA Colloquium Conference (October 1967)

In view of the recent interest in X-ray measurements of galactic sources, it is important to obtain a cogent physical model of the sources of such radiation. The Crab Nebula offers a unique opportunity for such a study since it is by far the best known source of radiation other than the sun. The astronomical evidence on the Crab Nebula is reviewed. The picture that emerges is that of a shell of matter arranged in a network of filaments (line emission) that carries electrical currents. The resulting magnetic fields enclose an amorphous plasma (continuum emission) embedded in which there are also two localized sources: the X-ray source and the low-energy, small diameter source. The wealth of details available warrants the study of detailed models, and the calculation of radiation in the bands not yet investigated.

6. The Electromagnetic Radiation Associated with the Energy Dissipated by Cosmic Rays in Interstellar Hydrogen by V. K. Balasubrahmanyan, E. Boldt, R. A. R. Palmeira, and G. Sandri

Presented at the Calgary Conference, (June 1967)

Evidence is presented for an interstellar cosmic ray spectrum that arises from a source function which is a power law in kinetic energy per nucleon ($\alpha E^{-2.5}$) and which gets modified by the energy degradation of particles that traverse an average 3 - 6 g/cm^2 of interstellar matter, with paths distributed according to a steady state model (Cowsil et al., 1966). For the interstellar spectrum inferred, the Coulomb interactions of cosmic rays with the hydrogen atoms of HI clouds are found to supply the correct energy input for maintaining at steady state the observed gas temperature of 10^2 ^oK . These interactions give rise to a high electron concentration ($\sim 10^{-1}$ cm^{-3}) , consistent with observations. The galactic background of X-rays and Hα radiation are shown to be measures of the electromagnetic interactions of cosmic rays with the hydrogen atoms of HI clouds.

7. The Electromagnetic Radiation Associated with the Energy Dissipated by Cosmic Rays in Interstellar Hydrogen, II by V. K. Balasubrahmanyan, E. Boldt, R. A. R. Palmeira, and G. Sandri

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The temperature observed ($\sim 10^2$ ^oK) for the hydrogen atoms of interstellar HI clouds is shown to be a consistent measure of the Coulomb interactions of cosmic rays. These interactions could also give rise to a high electron concentration ($\sim 10^{-1}$cm^{-3}) . The expected intensity of Hα emission by the hydrogen atoms excited by cosmic rays is found to be comparable to, but less than, that measured from the galactic disc. The inner bremsstrahlung X-radiation by electrons ejected from interstellar hydrogen atoms is indicated as a direct measure of the spectrum of the cosmic rays responsible for the ionization. A detailed study of the nonstellar X-rays from HI clouds is recommended for the determination of the spatial and spectral distribution of the low energy ($< 10^8$ e.v./ nucleon) cosmic rays that propagate throughout the galactic disc.

8. Cosmic Rays and the Temperature of H_I Clouds by V. K. Balasubrahmanyan, E. Boldt, A. Klimas, and G. Sandri

To be presented at the New York APS Meeting (November 1967)

The observed temperature of 100 ^oK for the hydrogen atoms of interstellar H_I regions may be accounted for by the heating caused by low-energy cosmic rays. At steady state the required energy deposition is 3×10^{10} ev/gram-sec. Considering the entire mass of interstellar gas in the galaxy, this energy deposition is compared with the estimated mean output of supernovae as the source of cosmic rays in the galaxy.

9. Relativistic Theory of N-bodies in External Electromagnetic Fields by A. Klimas and G. Sandri

To be presented at New York APS Meeting (November 1967)

A Lorentz invariant theory for the relativistic motion of N-charged particles (cosmic rays) in the presence of an external electromagnetic field is formulated and discussed. An N-body Hamiltonian is given which determines the evolution of the system of particles in terms of the single parameter, σ, introduced earlier (see 4). Similarities and differences with nonrelativistic statistical mechanics are discussed.

10. Solutions for Relativistic Two-body Equations Interacting through a Scalar Potential by G. Sandri and A. Klimas

To be presented at New York APS Meeting (November 1967)

We show that the relativistic equations of motion given previously (see 4) can be solved for simple interaction potentials. Square wells and power laws are discussed in detail.

The study of cosmic rays indicates the need for detailed information about the Galaxy. The following work has been carried out in this direction.

11. Review of Selected Topics on Galactic Structure Relevant to Cosmic Rays by A. Klimas and G. Sandri

ARAP Report No. 93

We summarize here the basic features of the Galaxy, geometric, dynamic, and physical, with particular emphasis on those aspects that are pertinent to the understanding of the cosmic ray spectrum and distribution. Contents: I, Introduction; II, Stellar Population; III, Interstellar Medium; IV, The Galactic Magnetic Field; V, The Halo; VI, Novae.

12. On the Possibility of a Noncosmological Explanation of the $3^{\circ}K$ Radiation by A. Klimas and G. Sandri

ARAP Tech. Memo. No. 66-6

The interesting suggestion has been recently made by Balasubrahmanyan, Boldt, and Palmeira that the radio wave $3^{\circ}K$ radiation may have a local explanation, the energy being supplied by cosmic radiation. In this note, we investigate the following simple model: high energy nucleons (the cosmic radiation) steadily supply energy to a medium within which the earth is embedded. The medium is assumed to be in thermal equilibrium and to radiate as a

black body. We show that for this model the interstellar gas of the Galaxy, or the intergalactic gas of the "local supergalaxy" can both radiate at approximately the same temperature (10^{-1} °K) if the cosmic ray energy is appropriately converted.

13. Notes from the 1967 Texas Symposium on Relativistic Astrophysics by A. Klimas

ARAP Tech. Memo. No. 67-2

This report contains a collection of notes taken from talks given at the 1967 Texas Symposium on Relativistic Astrophysics which was held in New York City in January 1967. The notes are designed to be useful to those readers who are intimately associated with the subject matter, and who might refer to them before the symposium proceedings are published. In this spirit, the notes have been kept brief; no references or background material appear, and no explanations of symbols are given unless they are not commonly used.

14. On the Possibility of a Radial Expansion of the Galactic Gas Disc by A. Klimas

ARAP Tech. Memo. No. 67-1

Models of the galactic gas disc have been constructed from 21-cm data under the assumption that the gas carries out pure circular motion about the polar axis of the Galaxy. However, there are indications of a small radial flow in the gas disc also. In this note, the possibility of a radial flow is examined further. It is shown that the radial flow expected from (1) the observed radial flow in the central region of the gas disc, and (2) the conservation of mass in a quasi-steady state flow in the outer disc is in substantial agreement with the corrections needed to eliminate the difficulties in the circular flow models. The magnetic field configurations which are possible in this "galactic wind" are derived. A natural explanation for the observed magnetic "neutral sheet" arises from this analysis.

15. Unpublished Work

An unpublished analysis of magnetic Brownian motion has begun in collaboration with Professor E. Nelson of the Institute for Advanced Study in Princeton, New Jersey.

Attention has been given recently to plasma effects in connection with cosmic ray phenomena. In collaboration with Professor Lam we are investigating the effect of a number of plasma modes on the energy and radiation character of cosmic electrons and protons.